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Water regimes and bean cultivar effects on the soil porous system characteristics

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***Abstract*— *Bean (Phaseolus vulgaris L.) is a crop of great economic and social impacts in Brazil. This crop is extremely appreciated by the Brazilian population and an important source of protein. Usually the small farmers are responsible by the largest production of the bean in Brazil. This work deals with the analysis of the effect of different water regimes (35, 28, 21 and 14%) on the porous system of a soil cropped with two distinct cultivars (Campos Gerais and Tuiuiú). Soil water retention curve (SWRC) and its derivative were utilized with the aim of investigating the changes in the porous system. Pore size distribution was also evaluated. The experiment was carried out at a greenhouse and the soil water content for the different water regimes was monitored by means of a TDR. Four undisturbed samples were collected from each wooden bed (eight) for the physic-hydrical characterization. Discrepancies in the SWRC were noticed for the region of small pressure heads. Differences were not observed between bean cultivars to SWRC. However, the water capacity function was sensitive to show differences in the soil porous system due to the treatments and cultivars. The lowest water regimes promoted the highest volume of fissures (big pores >250 µm) and, consequently, the highest ones had the largest volume of storage pores (<25 µm).*
Keywords*— *Phaseolus vulgaris L; water content; soil water retention curve; pore size distribution.

I. INTRODUCTION

Bean (*Phaseolus vulgaris* L.) is a crop that occupies a remarkable economic relevance in Brazil (Carvalho et al. 2014). This crop can be cultivated practically in all regions of the country, even under water and temperature restriction conditions (Silva et al. 2017). Brazil has a production of over 3 million of tons with an average yield of 1013 kg ha^{-1} (2014-2015) (Conab 2016).

The soil porous system is strongly influenced by its physical properties (Fernández-Ugalde et al. 2009; Basso et al. 2011), which can be used as quality indicators. For instance, soil bulk density (BD) or total porosity (TP) evaluations allow for a better comprehension of the changes in the soil structure due to anthropogenic and natural activities (Spera et al. 2009; Silveira et al. 2011).

Another major physical property of the soil is the water content, which indicates the ideal conditions for the most appropriate soil management (Mantovani et al. 2009). Such a property is also very meaningful for studies dealing with water retention and movement at a given site (Bernardo et al. 2006).

Soil water regimes are directly related to the frequency of wetting and drying (W-D) cycles. A large number of irrigation occurrences are necessary to maintain the soil with an ideal amount of water; consequently, the porous system is submitted to a large number of W-D events. Sequences of W-D can affect the physical properties of the soil, mainly those dependent on the distribution of pores (Pires et al. 2005; Pires et al. 2008).

The pore size distribution (PSD) can be derived from the soil water retention curve (SWRC), which is an important physical attribute that relates the pressure head and water content between themselves (Reinert & Reichert 2006). SWRC is a robust indicator of soil physical quality, and its data (available water, field capacity, permanent wilting point) allow for a more rational and ecological management of the soil in order to maximize crop yield in production fields (Centurion & Andrioli 2000; Silva et al. 2010; Debnath et al. 2012; Pires et al. 2017).

PSD obtained indirectly from the SWRC is also a parameter that can be utilized for a better comprehension of the water storage and movement, which is relevant for the root system development (Kutílek & Nielsen 1994; Hillel

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1998; Kastanek & Nielsen 2001; Lipiec et al. 2006). Through PSD, information about the volume of storage and transmission pores might be assessed. These pores are linked to the transmission and retention of water process, which are pivotal for the water storage for the plants and plant yield.

The objective of the study reported herein was to evaluate the effect of four water regimes on the porous system of a soil cropped with two different bean cultivars in Southern Brazil. The soil porous system was characterized by measurements of the soil water retention curve and pore size distribution.

II. MATERIAL AND METHODS

This study was carried out at a greenhouse of the Agricultural Research Institute of Parana (IAPAR) at the city of Ponta Grossa, PR, Brazil (25°06'S, 50°10'W, 875 m above sea level), throughout the year of 2016 with eight wooden beds (2.50×1.25 m).

The soil is classified as Ferralsol, according to the world reference base for soil resources (FAO, 2006), as Rhodic Hapludox, according to the USDA Soil Taxonomy (Soil Survey Staff, 2013) and as Dystrophic Red Latosol, according to the Brazilian Soil Classification System (Santos et al. 2013). The soil presents a clay texture (158 g kg^{-1} sand, 302 g kg^{-1} silt, 540 g kg^{-1} clay).

Disturbed soil samples were collected at the surface layer (0-20 cm) from an experimental field subjected to plowing and harrowing procedures. Soil sieved in an 8 mm-mesh was used to fill up the wooden beds. Each wooden bed had six spaced row at 40 cm with 12 plants per row. Each row had one single drip strip with eight emitters disposed at 15 cm each one with a maximum outflow per dripper of 1.4 L h^{-1}.

Two treated seeds per hole were manually sowed and after the emission of the first tree leaves roughing was done to allow only one plant per hole to remain in the wooden beds. Two different genotypes (Campos Gerais and Tuiuiú) of beans were utilized in this study. Soil fertilization was performed at sowing date with 19.5 g per row of the 4-14-8 NPK formulation. At 25 days after emergence (DAE) nitrogen fertilizer was applied in bands at a rate of 7 g of urea row.

The soil inside the wooden beds was submitted to four regimes of soil water content (35, 28, 21 and 14% at volumetric basis). The treatments (cultivars and water regimes) were allotted completely randomized in a 2×4 factorial experiment with 4 replications. Soil water contents within the stipulated irrigation water levels at this trial were monitored by means of a Time Domain Reflectometer (TDR) from Hydrosense (Table 1). All wooden beds received the same amount of water (66 mm) during the initial development stage of the crop.

After the final cycle of the crop, undisturbed soil samples (n=4) were obtained by using an Uhland sampler. Samples were collected by using innox cylinders (5×4 cm height and internal diameter) up to a depth of 7.5 cm.

The undisturbed soil samples were saturated by the capillary rise method and submitted to the following pressure heads (h): -1, -2, -4, -6 and -10 kPa (suction table, Heijkamp®, model M-0801) and -30, -100, -400 and -700 kPa (in pressure chambers, Soil Moisture Equip. Corp.®, model 1500) (Klute, 1986). The water content at the permanent wilting point (-1500 kPa) was theoretically predicted by the mathematical adjustment of the SWRC.

After thermodynamic equilibrium reached for each pressure head, the moist soil mass was evaluated and the dry soil mass was obtained in a forced air circulation oven (105 °C / 48 h). The volumetric water content was determined by multiplying the gravimetric water content by the soil bulk density assessed for each treatment and depth studied (Lal and Shukla 2004).

The SWRC experimental data were fitted by using the mathematical model proposed by van Genuchten (1980) in the SWRC Fit computer program (Seki 2007). The Mualem restriction was employed (Mualem 1976):

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + (-\alpha\, h)^n]^m} \qquad (1)$$

where θ_s and θ_r are the saturation and residual soil water content, respectively; h is the matric potential; α, n and m ($=1-1/n$) are empirical parameters that govern the shape of SWRC. The SWRC adjustments were obtained based on average values of θ (n=4).

After SWRC mathematical adjustments, the volumetric water capacity (C_θ) was obtained by means of the following equation (Radcliffe & Simùnek 2010):

$$C_\theta = \frac{\alpha^n(\theta_s - \theta_r)mn(-h)^{n-1}}{\left[1+(-\alpha h)^n\right]^{m+1}} \quad , \qquad (2)$$

where θ_r and θ_s denote soil residual and saturated water contents, respectively. The equivalent cylindrical soil pore radii (r) were obtained in µm with h expressed in kPa ($= 149/h$).

Relative differences (RD) were calculated by:

$$RD\% = \left(\frac{X_i - X_{i-1}}{X_i}\right).100 \quad , \qquad (3)$$

where X_i represents the soil attribute evaluated, e.g., θ or C_θ.

The influence of the treatments on the structure of the soil was also scrutinized taking into account soil pore classification systems based on functional characteristics. The system proposed by Greenland (1977) was used for this purpose, in which pores with equivalent cylindrical radii

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<0.25 µm are considered bonding + residual pores; ranging from 0.25 to 25 µm storage pores; varying from 25-250 µm transmission pores; and >250 µm comprise fissures.

With regard to the statistical analyses soil bulk density (BD), total porosity (TP), macroporosity (MA) and microporosity (MI) were subjected to Shapiro-Wilk test ($p<0.05$) for assesment of normality of the data. Moreover, ANOVA with application of F test along with S-N-K test ($p<0.05$) for two beans cultivars, and regression analyses for soil water regimes were performed herein.

III. RESULTS AND DISCUSSION

Soil physical attributes

The soil physical attributes BD, TP and macroporosity (MA) were influenced by the bean cultivars and water regimes, while the microporosity (MI) was affected only by the water regimes (Figures 1 and 2). The Campos Gerais cultivar provided higher BD and lower TP and MI than the Tuiuiú cultivar ones (Figure 1).

Under the studied soil water regimes it was verified linear effects on BD, TP, MA and MI. By this way, an increase in the water regimes means increases in BD and TP and decreases in TP and MI (Figure 2). These results give some idea about the importance of the W-D cycles caused by the water regimes (Table 1) in the process of soil structuration (Pires & Bacchi 2010).

By considering the initial condition of the unstructured soil, the effects of the largest soil water contents can be ascribed to the capillary forces acting in the formation of inter-aggregate bridges (Aluko & Koolen 2000; Viana et al. 2004; Ogunwole et al. 2015).

Soil water retention characteristics

Regardless of the bean cultivar, it was noticed tendencies among the SWRCs under the different soil water regimes (Figure 3). The highest soil water regimes (35 and 28%) showed water retention levels similar between them and such regimes were then characterized by the highest θ throughout the whole curve in comparison with the lowest soil water regimes (21 and 14%). The latter thresholds also brought about similarities in water retentions between them (Figures 3a and 3b).

For the Campos Gerais cultivar only slight differences were observed in the water retention for the highest pressure heads (Figure 3a). The water retention was practically the same between the treatments 21 and 14% (RD < 3%). Within the range of smaller pressure heads the treatments 35 and 28% resulted in a larger θ. In this case, RD was larger than 10% for the water regimes 35 and 28% in comparison with 21 and 14% (Figure 3c). Such an outcome is coherent with the largest MI and BD observed under both treatments (Figure 2) as a result of the rearrangement of the microaggregates and soil particles due to the W-D cycles (Pires & Bacchi 2010; Ogunwole et al. 2015).

For the Tuiuiú cultivar similarities in water retention were evidenced under the highest pressure heads among treatments, except for the 35% water regime (Figures 3b and 3d). The driest SWRC region presented similar results as to Campos Gerais cultivar, that is, a higher θ under the highest soil water regimes. This response is related to the highest MI and BD found under the highest soil water regimes (Figure 2). Similarities in θ near saturation are mainly linked to slight differences in TP and in specific parameters of the SWRC mathematical adjustment (Table 2).

The samples subjected to the highest water regimes had greater values of MI (Figure 2), which is one of the causes of the highest amount of water retained in the driest SWRC region, as previously mentioned. The soil under the lowest water regimes revealed a larger MA (Figure 2), indicating an easy drainage capacity when compared to the soil under the highest water regimes (Hillel 1998; Lal & Shukla 2004).

It is pertinent to mention that the water retention process is directly influenced by the soil texture, structure and organic matter content (Dexter et al. 2004). According to Rawls et al. (1991), such a process under the highest pressure head occurs mainly by capillarity, being, therefore, extremely governed by the arrangement of the soil particles owing to the presence of structural pores (Kutílek 2004; Kutílek et al. 2006; Lipiec et al. 2007; Pires et al. 2017). However, under the lowest pressure head the soil texture and its mineralogy become quite important due to the water adsorption process (Gupta & Larson, 1979; Machado et al. 2008). As in this study, once the soil used to fill up the wooden beds was the same, there are no differences in its texture and mineralogy that could explain the discrepancies observed within the driest region of the SWRC.

Pore size distribution

By analyzing the interactions between cultivars and soil water regimes, it can be seen that the water regime 35% revealed some similarities in C_θ, with the most frequent pore size similar between cultivars and a frequency of pores slightly larger for Tuiuiú. Under the 28% soil water content, the Tuiuiú cultivar had a larger frequency of pores in comparison to Campos Gerais and a shift of the most frequent pore within the region of larger pores (Figures 4a and 4b).

Regarding C_θ for the Campos Gerais cultivar, it was observed a large frequency of pores within the lowest soil water regimes (Figure 4a). There is also a shift in the most frequent pore within the region of higher sizes under the lowest water regimes. These results are directly related to the values of BD, TP, MA and MI (Cássaro et al. 2008;

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Ogunwole et al. 2015). Under the highest water regimes (28 and 35%) there are small differences in C_θ (RD < 10%) (Figure 4c), which is an indication that under such regimes, the soil porous system is quite similar between both treatments.

For the Tuiuiú cultivar, the size of the most frequent pore is practically the same under water regimes of 28 and 14%, along with a slight shift for the largest pore sizes in comparison to 35 and 21% (Figures 4b and 4d). Similarities were noticed between both cultivars with the largest frequency of pores belonging to the lowest water regimes. Therefore, for the Tuiuiú cultivar only small differences were observed in C_θ under water regimes of 28, 21 and 14% (Figure 4d), differently from what was observed for the Campos Gerais cultivar (Figure 4c).

The results obtained under water regimes of 21 and 14% can be explained by the small number of W-D cycles applied to the soil. The increase in the number of W-D cycles causes an increment in the rearrangement of the soil particles and micro aggregates and, as a consequence, BD and MI increase and MA decrease (Nolla 1982). Therefore, C_θ suffers a decrease with the increase in the number of W-D cycles, which points out that the soil when subjected to distinct W-D cycles turns out to be a target of important changes in its structure (Pires et al. 2005; Pires et al. 2008).

Finally, an analysis of the soil pore size distribution based on the Greenland classification was also carried out herein (Greenland 1977). For the Campos Gerais cultivar, the water regimes of 35 and 28% demonstrated a decrease in the volume of big pores (fissures) as opposed to the 21 and 14% soil water content (Figure 5a), which in turn are responsible for the water infiltration process (Kutílek & Nielsen 1994; Libardi 2005). However, an increase in the volume of storage pores (< 25 µm) was found under the 35 and 28% soil water treatments. Similarities in the volume of pores responsible for the redistribution of water (25-250 µm) within the soil profile were observed among soil water regimes (Figure 5a).

For the Tuiuiú cultivar, there is only a slight difference in the proportion of transmission and fissures pores among the water regimes of 28, 21 and 14% (Figure 5b). The treatment 35% presented a decrease in the volume of big pores (fissures) in comparison to the other treatments and a slight increase in the volume of transmission pores. It was also observed that the water regimes of 35 and 28% had the largest volume of storage pores (Figure 5b).

The comparison between cultivars (Figures 5c to 5f) showed that the water regimes of 35 and 28% were characterized by the most significant differences in the pore size distributions between cultivars. For all soil water regime treatments volume of fissures was higher for the Tuiuiú cultivar. In contrast, volume of storage pores was to be higher for the Campos Gerais cultivar, mainly under soil water regimes of 35 and 28%.

IV. FINAL CONSIDERATIONS

The findings here indicate that for the driest region of the soil water retention curve under the highest soil water regimes (35 and 28%) presented the highest water retention for both Campos Gerais and Tuiuiú cultivars. However, there are no great differences in water retention between cultivars. The most consistent differences were observed at the high values of pressure head mainly under the 35 and 28% soil water regimes.

The derivative of the SWRC was a parameter more sensitive to evidence differences in the soil porous system due to the treatments. For both cultivars, the frequency of pores was larger under the lowest water regime (14%). It was also noticed that the Tuiuiú cultivar was featured by a large frequency of pores under all soil water regimes studied.

Concerning the pore size distribution based on the functional characteristics of the pores both cultivars have showed a large volume of big pores (fissures) under the lowest water regimes. Yet, the highest water regimes were yoked to a large volume of storage pores. Nevertheless no significant differences between cultivars were detected.

Thus, considering that in the beginning of the experiment the soil presented a predominance of big pores owing to sieving, we can infer that the lowest water regimes (mainly 14%) had a null contribution to the soil structuration process. These results give some insights about the adequate water availability for the re-structuration of the soil under the action of wetting and drying cycles.

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TABLES

Table.1: Number of irrigation events (wetting and drying cycles) and the total irrigation water levels for the different soil water regimes

Cultivar	Number of irrigations			
	35%	**28%**	**21%**	**14%**
Campos Gerais	22	15	7	4
Tuiuiú	19	21	10	10
	Total irrigation water levels			
Campos Gerais	216	155	80	25
Tuiuiú	232	263	113	107

Table.2: Parameters of the mathematical adjustment of the soil water retention curve for each cultivar (Campos Gerais and Tuiuiú) and soil water regimes (35, 28, 21 and 14%)

Cultivar	Level	θ_s	θ_r	α	n	R^2
Campos Gerais	35	06339	02369	1978	1414	0997
	28	06266	02225	1805	1408	0998
	21	06473	02062	2606	1436	0999
	14	06452	01977	3347	1377	0999
Tuiuiú	35	06634	02096	2279	1374	0999
	28	06590	02072	3586	1359	0999
	21	06590	02092	3076	1444	0999
	14	06632	02058	3552	1446	0999

θ_s: saturated volumetric water content; θ_r: residual volumetric water content; α and n: adjustment parameters; R^2: coefficient of determination

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FIGURES

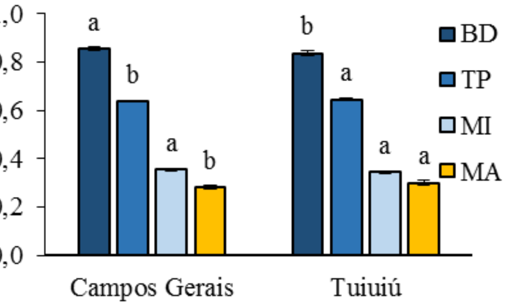

Fig.1: Soil buk density (BD), total porosity (TP), macroporosity (MA) and microporosity (MI) of the soil under the influence of two bean cultivars (Campos Gerais and Tuiuiú) Different letters mean statistic differences by the S-N-K test (p<005)

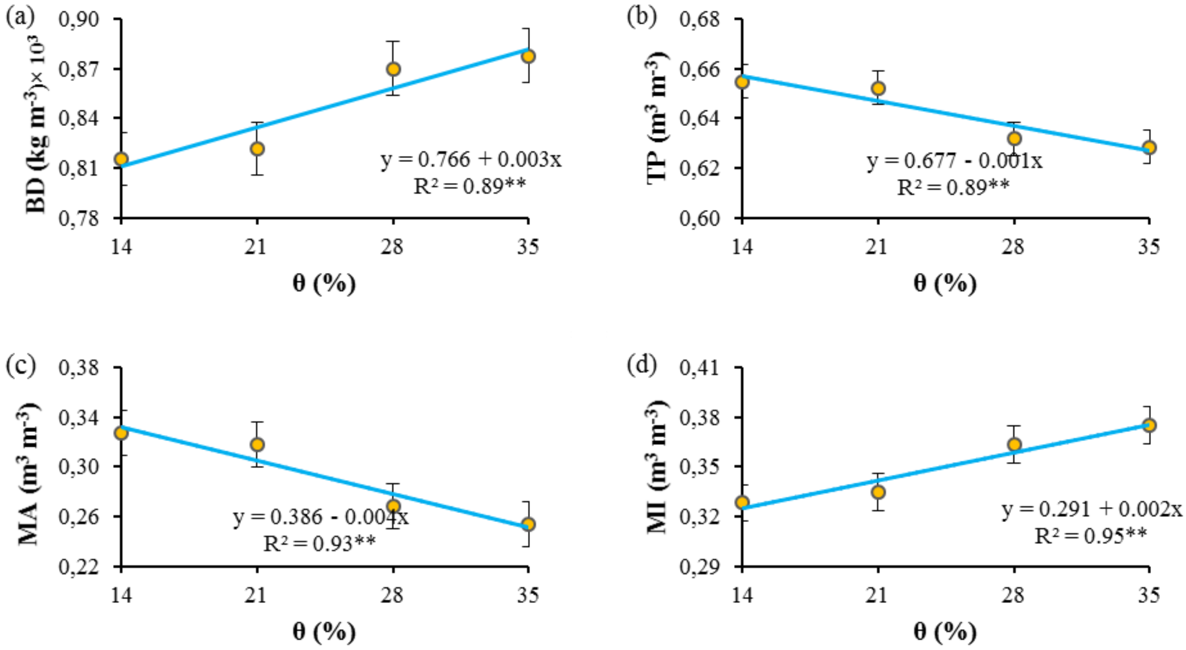

*Fig.2: Soil bulk density (BD) (a), total porosity (TP) (b), macroporosity (MA) (c) and microporosity (MI) (d) as a function of different soil water regimes (θ) (35, 28, 21 and 14%) **Signficance at p<0,01*

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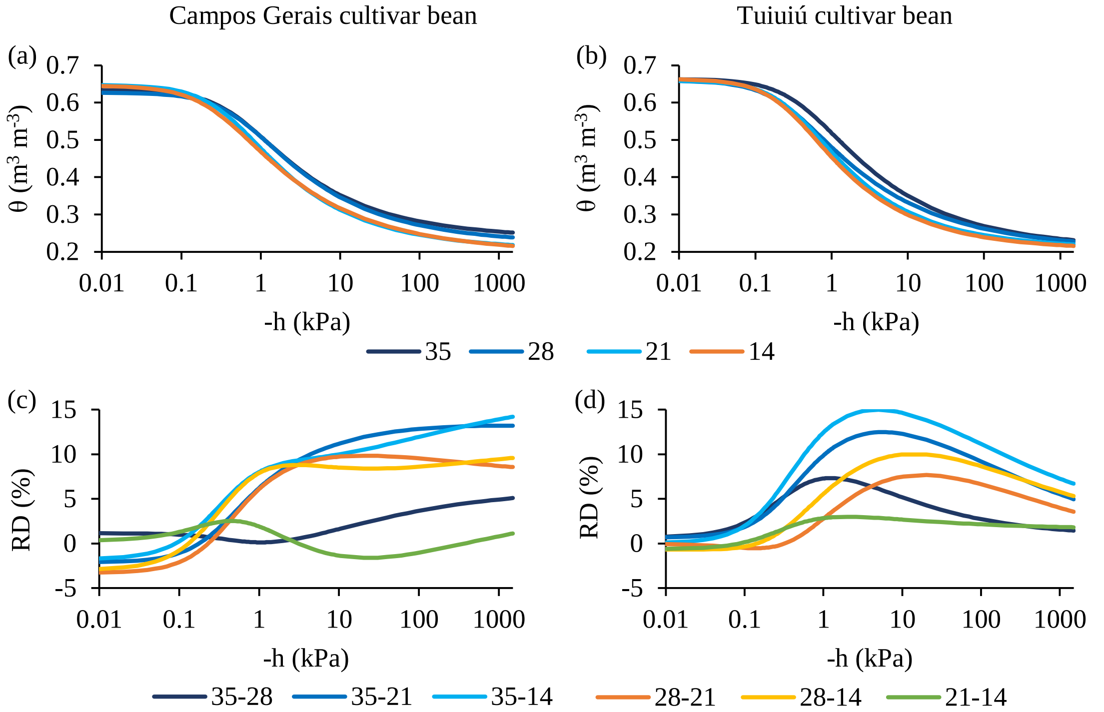

Fig.3: Soil water retention curves (SWRC) (a,b) for the bean cultivars Campos Gerais and Tuiuiú as a function of different soil water regimes (35, 28, 21 and 14%) along with relative differences (RD) among SWRCs for each cultivar (c,d) RD was calculated taking into account the highest soil water regime as a reference

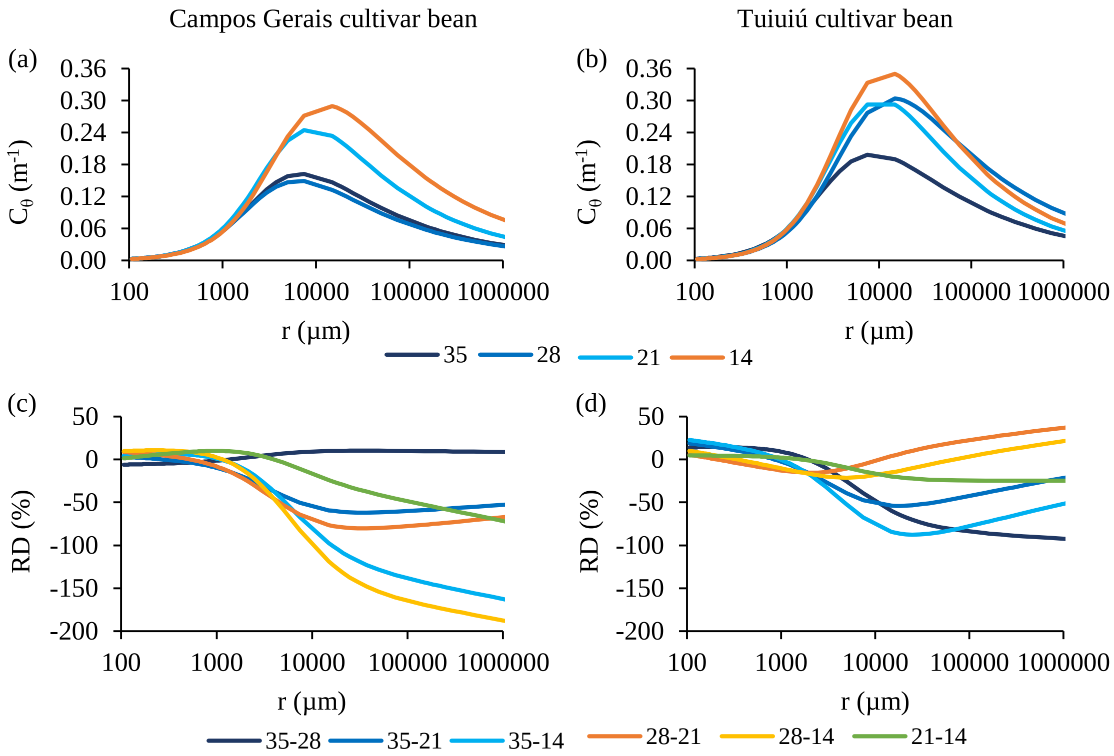

Fig.4: Volumetric water capacity (C_θ) curves (a,b) for the bean cultivars Campos Gerais and Tuiuiú as a function of different soil water regimes (35, 28, 21 and 14%) and relative differences (RD) among C_θ for each cultivar (c,d) RD was calculated taking into account the highest soil water regime as a reference

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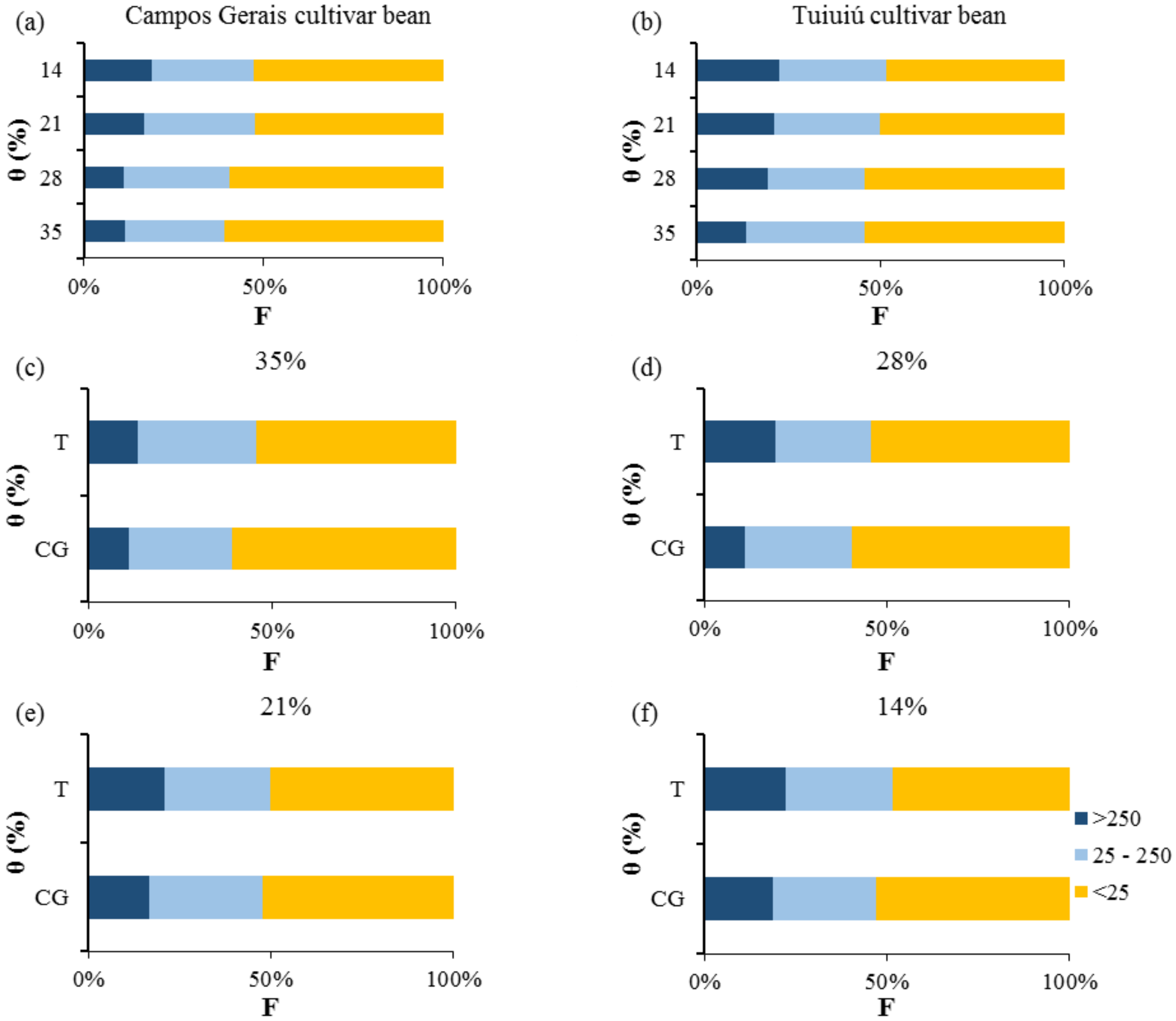

Fig.5: Frequency of pore sizes for the Campos Gerais (CG) (a) and Tuiuiú (T) cultivar beans (b) plus comparison between cultivars under different soil water regimes: 35% (c), 28% (d), 21% (e) and 14% (f) Three different pore size categories were evaluated according to the classification of Greenland (1979)